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A SYSTEM FOR MAPPING SOURCES OF VHF AND ELECTRIC FIELD PULSES FROM IN-CLOUD LIGHTNING AT KSC

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ABSTRACT

The literature concerning VHF radiation and wideband electric fields from in-cloud lightning is reviewed. VHF location systems give impressive radio images of lightning in clouds with high spatial and temporal resolution. Using systems based on long- and short-baseline time-of-arrival and interferometry workers have detected VHF sources that move at speeds of 10^5-10^8 m/s. The more slowly moving sources appear to be associated with channel formation but the physical basis for the higher speeds is not clear. In contrast, wideband electric fields are directly related to physical parameters such as current and tortuosity.

A long-baseline system is described to measure simultaneously VHF radiation and wideband electric fields at five stations at Kennedy Space Center. All signals are detected over remote, isolated ground planes with fiber optics for data transmission. The modification of this system to map rapidly-varying dE/dt pulses is discussed.

INTRODUCTION

The use of both direction finders and time-of-arrival techniques to locate VLF radiation from distant lightning is well-established (for example, [1,2] These early systems could locate general regions of lightning activity with a spatial accuracy of about the scale of a storm. When these techniques were applied to VHF and UHF from close lightning within about the last decade sources could be mapped with much higher resolution in both time and space. Consequently, we now have VHF radio images of lightning, frequently in three dimensions, with spatial resolution of up to a few tens of meters and temporal resolution of the order of microseconds. Proctor [3] describes a system that locates VHF sources from lightning in three dimensions with an optimal resolution of about 100 m vertically and 25 m horizontally. Proctor used five receivers with a center frequency of 250 MHz and a bandwidth of 5 MHz located on 30 km and 40 km baselines . He presents detailed descriptions of the VHF development in five cloud flashes [4], 26 consecutive flashes in relation to radar pictures [5], and 47 ground flashes [6]. A similar long-baseline system using time-of-arrival is reported by Lennon [7] whose data was analyzed in Rustan et al. [8]. Following Oetzel and Pierce 's suggestion [9] that line-of-sight direction finding was possible using much shorter baselines than Proctor's, hence obviating the problem of pulse identification at all stations when pulses arrive in different order at different stations, Cianos et al. [10] described a technique for two-dimensional location of VHF pulses at 30 MHz using stations separated by about 300 m with relative timing of about 10 ns. This technique was also implemented by Murty and MacClement [11] using sferics in the range 82-88 MHz. Taylor [12] reduced the distance between receivers to 14 m by increasing his bandwidth to 60 MHz (frequency range 20-80 MHz) and timing resolution to 0.4 ns and obtained three dimensional fixes by establishing two stations separated by several kilometers. Further results obtained by Taylor's system are reported in Taylor et al. [13] A variation on the short baseline method was developed by Warwick et al. [14] who, instead of measuring time differences between stations, used an interferometer to measure phase differences and two-dimensional locations for VHF at 34 MHz. The advantage of interferometry over long-baseline time-of-arrival is that the source location can be found in near real time, as opposed to many months later as reported in

Proctor [3], and the tracking of faster VHF sources is possible owing to the short (about 1-5 μs) time aperture needed for a single fix. Further results using this system are reported in Hayenga and Warwick [15] Hayenga [16] and Rhodes and Krehbiel [17]. An interferometer centered at 300 MHz has been described in Richard and Auffrey [18] and the results obtained have been discussed by Richard et al. [19], Mazur [20] and Bondiou et al. [21].

Wideband electric field measurements have been made with sufficient bandwidth to distinguish submicrosecond-scale variations by several workers within the last two decades. For a review of return stroke fields refer to Uman [22]. Wideband radiation electric field pulses from in-cloud processes have been observed in three distinct forms:- (i) bipolar pulses of about 40 μs full width with 2-3 fast pulses riding on the initial half cycle [23]; (ii) unipolar pulses with halfwidths of typically 0.75 μs that occur in regular sequences of 100-400 μs duration [24]; and (iii) bipolar pulses of about 10 μs halfwidth with smoother rise and smaller overshoot than those in (i) [25]. The Le Vine pulses were observed to accompany the largest amplitude rf noise at 3-295 MHz [25] and have 20 dB more spectral energy at 20 MHz than first return strokes [26].

Krehbiel et al. [27] describe a system for locating major charge transfers using a multiple station system with a bandwidth of close to DC to 1 kHz and give results for leaders, continuing currents and slow in-cloud processes in ground flashes. Despite the success of this method for ground flashes, Liu and Krehbiel [28] had difficulty interpreting the slow E fields after about 30 ms in intracloud flashes, presumably because of overlapping processes at different locations. Measurements of wider bandwidth electric fields have also been used to locate the strike point of return strokes by [7,29]. There are no reports in the literature concerning measurements of multiple wideband electric fields from in-cloud processes.

In this presentation we investigate the origins of VHF and wideband electric fields for in-cloud lightning processes, describe a system currently being implemented at KSC to measure and interpret these signals, indicate some important applications, and relate our recent results to the design of future high speed mapping systems.

ORIGINS OF VHF RADIATION

According to Proctor [3], the amplitudes of noise pulses at 250 MHz are not proportional to the charge lowered. Since some processes such as the dart leader tip did not radiate at all, Proctor concluded that "VHF noise occurs during the incipient stage of channel formation", a conclusion that was reinforced by his results for cloud flashes [4]. Proctor [3] differentiated between two types of discharge process in cloud flashes according to the VHF characteristics:- (i) new channel formation associated with VHF pulses: and, (ii) recoil streamers along existing channels that caused "Q noise". VHF pulses were emitted at rates from 10^3 to 10^5 pulses/second and were associated with sources that moved at speeds of 6×10^4 m/s to 10^5 m/s. Q noise trains lasted from 10 μs to over 2 ms and consisted of short pulses superimposed on a low frequency component that started and ended with gradual ramps lasting up to tens of microseconds. Q noise sources were deduced to be positive streamers, with one exception, and propagated at speeds of 2.7×10^6 m/s to 4.6×10^7 m/s. Proctor's figure showing how the Q noise was associated with the electric field waveshapes in one of the two K changes he showed is reproduced in Figure 1. The electric field antenna had a rise time of about 7 μs and a decay time constant of 100 μs. Note that in both this and the other case shown the VHF preceded the electric field rise and started ramping several tens of microseconds before the rapid portion of the K change. In his study of ground flashes, Proctor et al. [6] noted further that stepped leaders and intracloud streamers could not be distinguished, since both emit pulses and propagate at an average speed of 1.6×10^6 m/s. He found that his single-station 3.5 kHz bandwidth electric fields were consistent with a model in which

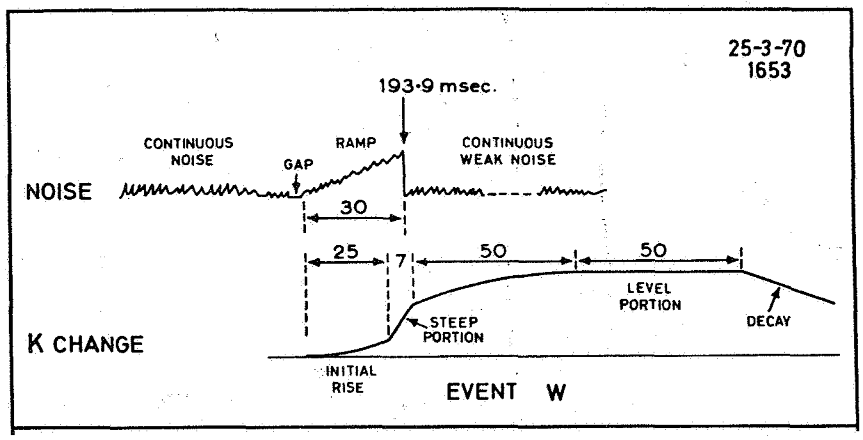

Figure 1. VHF noise and electric field change for a K change. Time intervals are in microseconds. Reproduced from Proctor [4].

charge is deposited at the position of the radio sources and depleted from the point of origin of each leader. Proctor et al. [6] found Q noise sources that propagated at 10^8 m/s during return strokes, and at a similar speed during interstroke periods. Individual components of these latter sources were directed vertically but there was an overall horizontal progression from one component to the next at an average velocity of 2.2 x 10^4 m/s horizontally away from the starting points of the flashes. The median duration of these Q noise trains was 80 μs and the median interval between them was 3.5 ms.

On the basis of interferometric measurements in a 3.4 MHz bandwidth centered at 34 MHz, Hayenga and Warwick [15] identified "acceleration of electrons in the high electric field at the tip of propagating breakdown streamers" as the source of VHF radiation in individual noise bursts, and a "propagation of the breakdown region" as the slower process responsible for the drifting motion from one burst to the next. During both the initial and intracloud portions of ground flashes, the bursts were typically 20 μs long, occurred about every 100 μs, extended about 1km in length, and propagated at about 5 x 10^7 m/s. Fast burst origins drifted at a typical speed of 2 x 10^5 m/s. Hayenga and Warwick show one cluster of fast bursts in the initial portion of a ground flash that appeared to move downward within bursts with a horizontal drifting from burst to burst. Hayenga [16] noted that fast bursts always accompanied K changes but also occurred when no K change was apparent. He considers his "fast bursts", Proctor's "Q noise" and the "solitary pulses" defined by Rustan et al. [8] to be the same phenomenon. Figure 2 is Hayenga's [16] locations, VHF power (rectified and integrated interferometer fringe output) and electric field for a typical fast burst. Note that the VHF precedes and overlaps the electric field pulse. Hayenga [16] identifies a further type of VHF source that is a precursor to dart leaders. These precursors moved into regions devoid of previous VHF in contrast to the bursts that travel through or on the edge of previously active regions. However, Hayenga cautions that the optical dart leader and the precursors are not correlated directly, although they are related, and therefore that the K change optical events (Brook and Kitagawa,1977) are probably not correlated directly with the VHF fast bursts.

Using an interferometric system with a 600 kHz bandwidth centered at 300 MHz [18], Richard et al. [19] classified VHF sources into two types depending on the rate of pulse emission. (i) Low-rate pulsed radiation with rates of 1-20 pulses/microsecond (1 x 10^6 to 2 x 10^7 pulses/s) consisted of pulses

usually narrower than 3 μs width in pulse trains with durations of up to several hundred milliseconds. (ii) High-rate bursts of radiation appear as "dense pulsed radiation lasting from a few tens of microseconds to 1 ms". They

associated the high rate bursts with recoil streamers and K changes in the last few hundred milliseconds of an intracloud flash when the VHF sources in each burst propagated at about 10^7 m/s over distances of a few to 10 km with

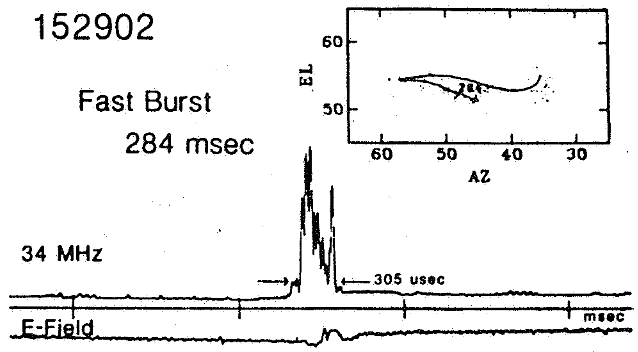

Figure 2. Loci of fast burst VHF movements. Postions within each burst were joined in their proper time sequence. Reproduced from Hayenga [16].

subsequent bursts following tens of milliseconds later along the same path. Mazur [20] noted that the radiation sources associated with K changes in the J-type stage of intracloud flashes originate in parts of the cloud where no radiation sources had been previously located and propagate towards the region of initiation. This observation contrasts with that of Hayenga [16] who observed fast pulses skirting or penetrated previously active regions. It is also different from the observation of Proctor [4] that most sources of Q noise were located near the flash origin and appeared to result from an overshoot of a wave that had returned along the main channel. Another major difference lies in Mazur's statement that "positive leaders are not detected by the interferometric system" in that Proctor [4] deduced that the sources of Q noise were positive streamers. Richard et al. [19] found decorrelations between electrical or optical discharge processes and sources of 300 MHz radiation, concluding that "the VHF-UHF electromagnetic phenomenolgy is distinct in some specific cases from the electric phenomenology". Specifically, they found higher velocities for VHF sources (10^7 m/s) than have been previously observed for the luminous streamer in K changes, development of radio sources down the leader channel before the leader's electric field change, and return stroke radio sources that were generally spread out along the leader trajectory or within the cloud with a lack of spatial correlation to the precursor activity. Labaune et al. [30] determined that VHF-UHF radiation sources that propagate at:- (i) 10^5-10^6 m/s correspond to the step and branching mechanisms of negative leaders; (ii) 2×10^7 m/s, the most commonly observed phenomenon, cannot be interpreted in terms of known properties of dry air discharge; and (iii) 10^8 m/s arise from mechanisms triggered in the channel corona envelope as an indirect consequence, but not the propagation of, the return stroke. Labaune [31] and Weidman et al. [32] both measured the wideband electric fields in the VHF-UHF range (10-500 MHz). The typical pulse obtained by Labaune is

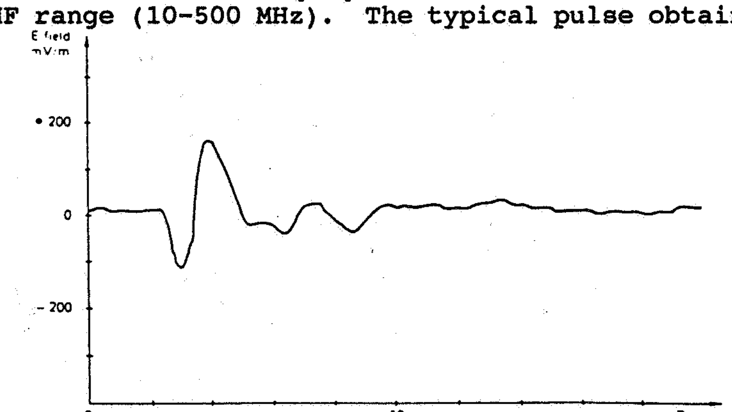

Figure 3. Broadband pulse typical of VHF-UHF radiation from lightning. Reproduced from Labaunne et al. [30].

given in Figure 3. This shows the short risetime of 5 ns that is consistent with the "streamer-leader" transition in negative streamers that Labaune et al.

[30] conclude to be the origin of VHF-UHF radiation. Similar measurements made by Weidman et al. [32], however, indicate risetimes of the order of 30 ns. Le Boulch and Hamelin [33] propose that Weidman's longer risetimes could be attributed to positive streamers.

IN-CLOUD ORIGIN OF WIDEBAND ELECTRIC FIELD PULSES

The bipolar pulses observed by Weidman and Krider [23] had fast (about 1 μs width) pulses riding on the intial half cycle. They interpreted these as indicating the formation of the discharge channel in some stepped fashion since the fast pulses were similar to those produced by stepped leaders [34,35]. The bipolar component was then produced by a slower current surge which flows either while the channel is being established or just after. Krider et al. [36] found a clear tendency for the rf radiation to peak during the initial half cycle of these pulses with the temporal development of the rf being similar for all frequencies in the range 3-295 MHz. They note that this observation is consistent with Weidman and Krider's interpretation since predischarge and leader processes do produce strong rf. Krider et al. [35] postulated that, for a stepped leader, a fast current pulse might propagate several hundred meters up the vertical leader channel before dissipating so that the radiation field E(t) in the first 1 or 2 μs is related to the current I(t) by

$$E(t) = (-\mu_0 v/2\pi D) i(t')$$

where v is the constant propagation speed, $t' = t - D/c$, and D is the horizontal distance to the base of the channel. This relationship is also valid for a vertical in-cloud current. Thomson [37] found a similar relationship for an in-cloud current pulse propagating along a channel of arbitrary orientation. Specifically, the radiation field was also proportional to the speed-current product with additional geometrical factors. Thomson [37] further found that four wideband radiation fields could be inverted to give the magnitude of the speed-current product, the current waveshape, and the direction of the velocity of propagation.

Krider et al. [24] interpret the trains of regular electric field pulses that they observed in terms of an intracloud discharge process similar to the dart-stepped leader. Noting a consistency between the speeds of dart-stepped leaders measured by Schonland et al. [38] and the speeds of streamers that produce K changes as suggested by Ogawa and Brook [39], they propose that "a significant fraction of any dartlike K changes develop in a stepped fashion and produce the observed uniform pulses". The 100-400 μs durations of these pulse trains is consistent with Proctor's median duration of 80 μs for Q noise that he attributes to K changes.

Le Vine [25] found that the strongest sources of rf radiation in the 3-300 MHz range were short duration (10-20 μs) bipolar pulses that did not have fast unipolar pulses riding on the intial half cycle. He noted no apparent correlation between strength of the RF radiation and the size of the associated E pulse. Le Vine modeled these pulses as a fast (10^8 m/s) K streamers that lower positive charge or raise negative charge. Subsequent results by Willett et al. [26] and Medelius et al. [40] indicate, however, that the Le Vine-type pulses are usually isolated and cannot be obviously attributed to any known lightning processes such as K changes.

The effect of channel tortuosity on wideband electric fields and radiation spectra was investigated by Le Vine and Meneghini [41,42]. Although they apply their model to a tortuous return stroke, their results are also applicable to a general current pulse propagating along an established channel. Le Vine and Meneghini [42] find that tortuosity renders the electric field waveshape less representative of the current pulse and more unipolar than theory predicts. Tortuous channels act as adjacent short channel lengths and behave mathematically as several point radiators located at the channel kinks. The

radiated waveform thus contains information on both the current waveshape and the channel tortuosity.

SYSTEM

The measurement system being constructed for this summer's experiment comprises five remote stations with two wideband channels (1 Hz to more than 8 MHz) per station. The remote stations are located at the eastern bank of the Indian river, the UC9 site on Playalinda Beach, Unified S-Band (USB), Hypergolic Maintenance Facility (HMF), and the central station is at the Shuttle Landing Facility (SLF). The distance beween remote and central stations is about 10 km. Signals are sent back to a central recording station via either microwave links with a carrier of 10 GHz and 3 dB bandwidth of 1 Hz-8 MHz, or analog fiber optics links with a 3 dB bandwidth of 1 Hz to 14 MHz. Control of all functions at the remote stations is an enhancement of the technique using two-way coded audio tones that is described in Thomson et al. [43]. Control functions include gain, antenna, and calibration of the electric field sensors, and power, signal switching (50 MHz or 225 MHz), and miscellaneous system status features such as adequate battery voltage. Synchronization of remote stations is effected using the timing signals inherent in any TV broadcast. We will use WESH TV 2 that broadcasts from Orlando at 55.25 MHz.

Electric field changes at each station are detected by integrating the displacement current intercepted by a flat plate antenna. The 10-90% rise time of these integrators is 40 ns and they decay with a 1 ms decay time constant to a step electric field input. Triangle-wave and square-wave calibration signals can be applied through a known capacitance directly to the inputs of the integrators to simulate a electric field for linearity and absolute field calibrations as shown in Thomson et al. [43].

VHF radiation is received in a 5 MHz bandwidth at a center frequency of both 50 MHz and 225 MHz. Detection is with an envelope detector and each signal is compressed with a logarithmic amplifier. Envelope rather than product detectors are used to decrease signal distortion that may arise in product detectors as a result of IF frequency shifts.

The five electric field signals sent back from the remote stations are recorded at the central station in digital form in a 5-channel 8-bit Le Croy digitizing system interfaced with an 80386-based IBM clone PC. The signals are digitized at 20 MS/s for 100 μs each time a trigger occurs. Consecutive trigger events are digitized sequentially with no dead time between triggers until the 128 kS Le Croy memory is full. Thus 64 trigger events can be recorded per lightning. The central channel has a 32 μs pretrigger delay so that the signal radiated by a single event is recorded somewhere in each 100 μs window. The electric fields are also recorded continuously on five FM channels of a Honeywell 101 magnetic tape recorder with 0-500 kHz 3dB bandwidth. The VHF signals, either 50 MHz or 225 MHz, are also recorded on the inner five channels of the seven tracks on a single headstack of our Honeywell magnetic tape recorder. Using DIRECT recording mode gives a bandwidth of 400 Hz to 2 MHz. The outer two channels of the headstack have modulated synchronization signals derived from WESH TV2 that are needed for deskewing the signals and providing accurate timing. Tape skew has proven to be an important problem in previous measurements of this type [44]. A common time code recorded in both the digitizer and tape recorder system is an amalgamation of IRIGB and TV synch signals that gives relative timing with 50 ns accuracy. Propagation delays along the microwave and fiberoptic links will be calibrated out by adding in to each channel either the horizontal synch signal (one pulse per 63 μs) or a high frequency code derived from the WESH TV2 signal.

The locations of the VHF and electric field pulses recorded by the system will be found from the differences in times of arrival as described by Proctor [3]. The radiation electric fields will also be inverted to give the current-velocity product for each pulse origin as explained by Thomson [37].

DISCUSSION

APPLICATION TO FAST PULSES

The above literature review indicates that a major problem revealed by VHF mapping systems is the interpretation of the physical origin of VHF sources that are observed to propagate at speeds of 10^7 m/s and faster. Whereas VHF sources that propagate at 10^5-10^6 m/s appear to be associated with ionization at the tips of extending streamers, the faster VHF sources are not attributable to known optical processes [28]. On the other hand, return stroke models relating electric field pulses to observed optical velocities and current waveshapes have been validated by experiment (for example, Willet et al., [45]). A straightforward extension of these models to in-cloud currents should yield results that are directly interpretable in terms of either the current propagation [37] or channel tortuosity [41,42]. By mapping both VHF and electric field pulse sources, as well as the current-velocity vector for each electric field pulse, we can investigate the physical relationship between these two signals. For example, if, as is proposed by Krider et al. [36], the VHF radiation preceding the electric field peak is associated with the formation of the channel while the electric field pulse arises from the current flow along that channel, we should detect an extending VHF source that is followed by a current-velocity vector originating at its tip and pointing back down the VHF extension. Similarly, if the small pulses riding on the leading edge of the bipolar pulses observed by Weidman and Krider [23] are also associated with the formation of the same channel that is the origin of the VHF pulses, then the locations and propagation directions of the sources of these pulses will be consistent with the movement of the VHF sources.

SYSTEM MODIFICATION FOR DE/DT MAPPING

The dE/dt record has many interesting features. The narrow bipolar pulses first noted by Le Vine [25] have significant dE/dt fine structure throughout the whole bipolar E waveshape [26] that is frequently so large as to obscure the derivative of the microsecond-duration E pulse [40]. This dE/dt fine structure arises from short-duration pulses that ride on top of the microsecond-scale E pulse waveshape. The zero crossings of this dE/dt "noise" occur at the peaks of the short-duration pulses. Figure 4 shows dE/dt recorded at a digitization rate of 100 MS/s. This figure shows that dE/dt has significant variations on a 10 ns scale. In fact, we have recently recorded dE/dt with a 400 MS/s digitization rate that indicates fine structure on a several nanosecond time scale. These pulses are undoubtedly those that are detected by VHF location systems operating in this range. The effect of filtering these dE/dt signals through a bandpass VHF receiver is discussed further in Medelius et al. [40]. In order to establish the relationship between the dE/dt fine structure and the microsecond duration E waveshape simultaneous mapping is needed. The best way to map the dE/dt is probably with a short baseline system similar to that described by Taylor [12]. However, we require a much faster location rate than one per 40 μs, as was obtained by Taylor. In fact, if all zero crossings are to be detected, a rate of one fix per few nanoseconds is desirable. Simultaneous mapping of E pulses and dE/dt would offer a powerful tool for investigating the nature of rapidly-propagating in-cloud currents, and these are precisely those whose VHF origins are least well understood.

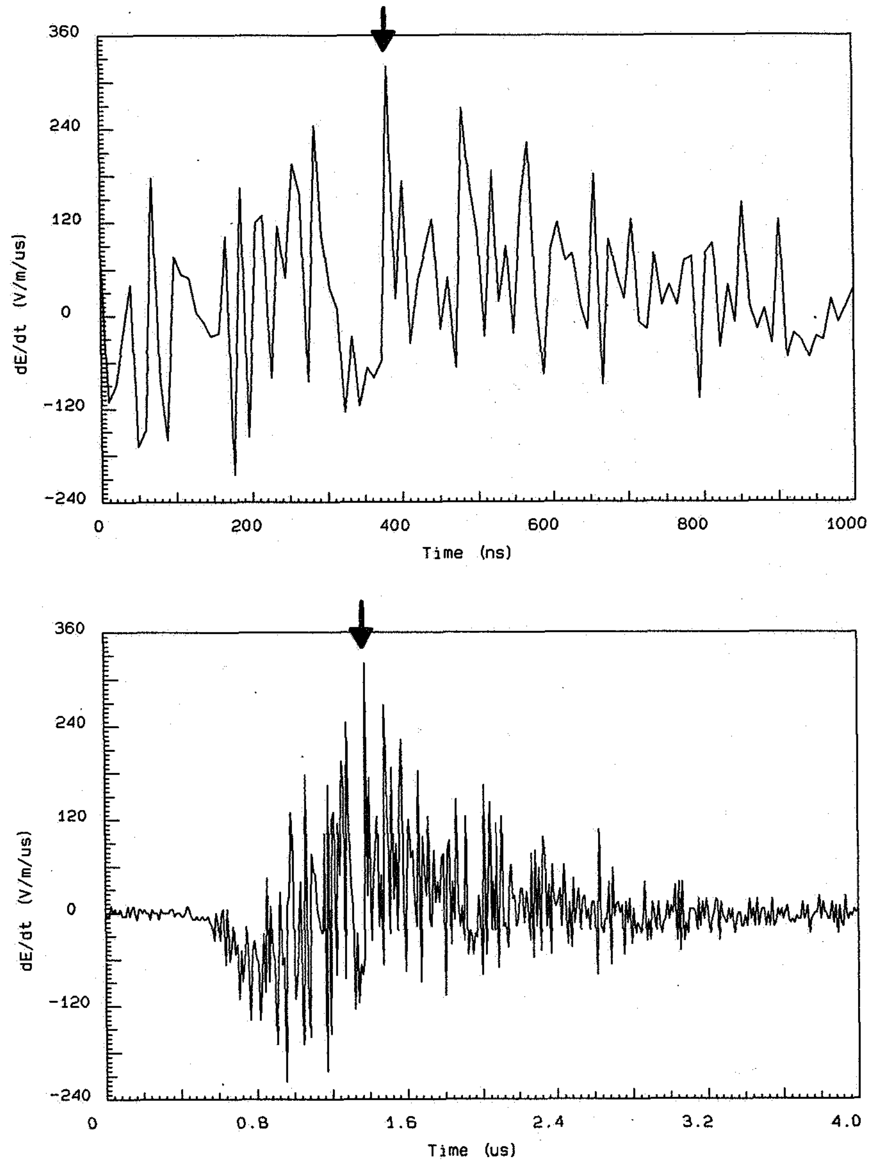

Figure 5. dE/dt waveshapes for a bipolar electric field pulse. The arrow indicates the same point on both traces.

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